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ASEISMIC ROOF ISOLATION SYSTEM: ANALYTIC AND SHAKE TABLE STUDIES

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SUMMARY

Presented are the features of a roof isolation system that is proposed as a device to reduce the seismic response of buildings. Presented also are the details of and results from analytical and experimental studies conducted with a small-scale laboratory model to assess the feasibility and effectiveness of such a device. The roof isolation system entails the insertion of flexible laminated rubber bearings between a building's roof and the columns that support this roof, and the installation of viscous dampers that are connected to the roof and a structural element below the roof. It is based on the concept of a damped vibration absorber and on the idea of making the roof, rubber bearings, and viscous dampers respectively constitute the mass, spring, and dashpot of such an absorber. The model considered in the analytical and experimental studies is a 2·44-m high, five-storey, moment-resisting steel frame, with a fundamental natural frequency of 2·0 Hz. In the experimental study the frame is tested with and without the proposed roof isolation system on a pair of shaking tables under a truncated version of one of the accelerograms from the 1985 Mexico City earthquake. In the analytical study, the frame is also analysed with and without such a system and under the same ground motion except that the ground motion accelerations are properly magnified to study the effectiveness of the roof isolation system when the frame is stressed beyond its linear range of behavior. It is found that the suggested device effectively reduces the seismic response of the frame, although the extent of this reduction depends on how large its non-linear deformations are. Based on these findings, it is concluded that the proposed roof isolation system has the potential to become a practical and effective way to reduce earthquake damage in low- and medium-rise buildings. Copyright © 1999 John Wiley & Sons, Ltd.

KEY WORDS: vibration absorber; tuned mass damper; passive control; protective systems; base isolation; damping system

INTRODUCTION

Vibration absorbers, consisting of a comparatively small mass-spring-dashpot system in resonance with the structure on which they are installed, have been shown to have potential to become a practical and effective way to protect structures against the effect of earthquakes. In studies conducted by the first author and his co-workers in the past several years,[1–4] it is found that, with an adequate selection of their mass and damping ratios, these devices may be quite effective in reducing the seismic response of buildings and other structures. It is also found, however, that

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they have some disadvantages as well. First, they require a relatively large mass, and, therefore, a large space for their installation. Second, they are susceptible to undergo large displacements in relation to the points of the structure to which they are attached since, by design, they are set in resonance with the structure. As a consequence, they also require a large additional space and the corresponding clearance to accommodate such large displacements. Lastly, they need to be mounted on a smooth surface to minimize friction forces and facilitate their free motion.

In an effort to overcome these disadvantages, the first author[5] has proposed to use the mass of a building's roof as the mass of the absorber. For this purpose, he has also proposed to mount a building's roof on elastomeric bearings and use viscous dampers to connect the roof to a structural element below the roof, such as it is shown in Figure 1 for a typical building. The idea is to make the roof, elastomeric bearings, and viscous dampers respectively constitute the mass, stiffness, and damping element that are needed to build such an absorber. In this manner, a building can be implemented with a vibration absorber without adding to the building a burdensome mass and without encumbering its roof space. Besides, it is possible to do it in a simple and cost effective way since the required construction is not too involved and the necessary elastomeric bearings and viscous dampers are commercially available.[6,7]

The first author has also made a preliminary assessment of the feasibility and effectiveness of the proposed roof isolation system by numerically analysing and comparing the response of a simple five-storey steel building when the building is and is not implemented with it.[5] In this analytical study and for this particular structure, it is found that such a detail is indeed effective in reducing the response of the structure. In a logical next step, the authors have now conducted a shake table experimental study with a small-scale model with the intention of (a) verifying without the assumptions and uncertainties involved in an analytical study that the proposed roof isolation system may also work effectively as a vibration absorber in a real structure; and (b) assessing the design and construction difficulties as well as the physical limitations associated with the implementation of such system. Owing to the limited capacity of the testing equipment and a desire to investigate the performance of the isolation system when the structure is stressed beyond its linear range of behaviour, the investigation also included a series of numerical

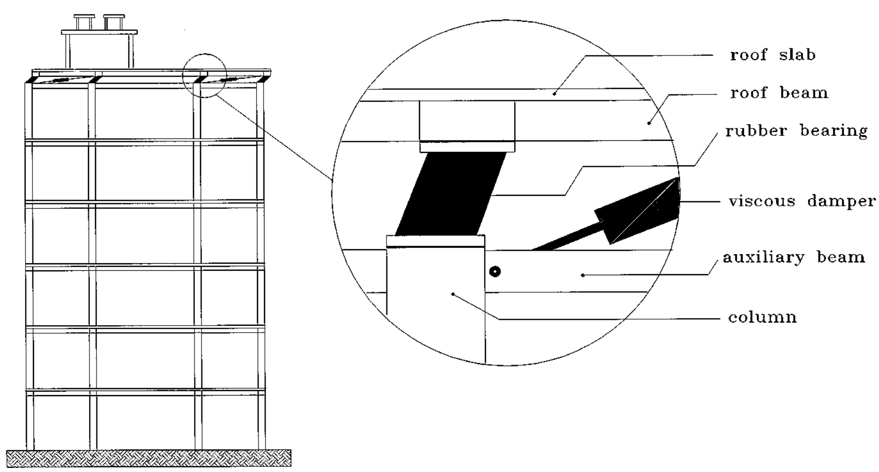

Figure 1. Typical building with proposed roof isolation system

simulations with a finite element model of the experimental model with such an aim in mind. It is the purpose of this paper to describe the details and results of these experimental and analytical investigations and the conclusions derived thereof.

EXPERIMENTAL MODEL

The model studied is depicted in Figure 2. It has five stories, a height of 2·44 m (8 ft) and a width of 0·91 m (36 in). It is built by welding its square columns to base plates, welding its longitudinal and transverse rectangular beams to the columns, and welding its rectangular secondary beams to the longitudinal beams. Its floor and roof plates are supported freely by all the beams, but are restrained against lateral motion by special keys welded to the inferior face of the plates. Cold-rolled structural steel with a yield stress of 517·5 MN/m^2 (75 000 psi) is used for the columns and the transverse beams. The longitudinal beams are built with hot-rolled structural steel with a yield stress of 248 MN/m^2 (36 000 psi). The moment of inertia and yield moment of the columns are 2169 mm^4 (0·00521 in^4) and 84·9 N m (750·2 lb in), respectively. The corresponding values for the longitudinal beams are 541 mm^4 (0·00130 in^4) and 21·8 N m (192·4 lb in). The total weight of the frame, without including its base plates, is 455·2 N (102·2 lb). Its top plate alone weighs 70·8 N (15·9 lb).

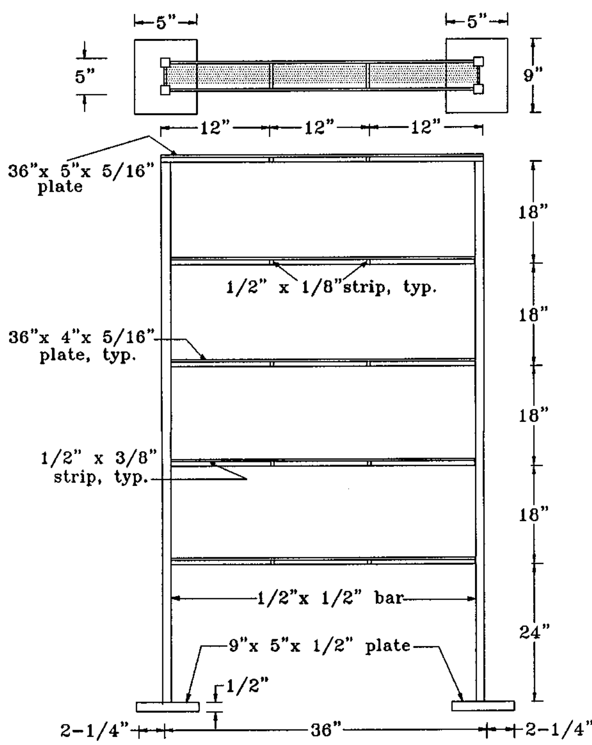

Figure 2. Five-storey steel frame model (Note: 1″ = 25·4 mm)

When the frame is implemented with the proposed roof isolation system, the top plate is mounted on four rubber bearings that are glued to the inferior face of the top plate and to base plates attached to the top of the frame's columns. In addition, four pneumatic cylinders, two at each of the longitudinal sides of the frame, are connected to the top plate and to the top transverse beams at the edges of the frame. Figure 3 shows a close-up view of the way the rubber bearings and dampers are mounted on the frame.

For the design for the rubber bearings, the modal properties of the frame without its top plate are determined numerically. For this purpose, the frame is modelled with linear beam elements, lumping its mass at its nodes, and assuming its columns fixed at the end connected to the base plates. The obtained natural frequencies, participation factors, unit-participation-factor generalized masses, and unit-participation-factor mode shape amplitudes at roof level for the first three modes are listed in Table I. As the fundamental mode is, as expected, the dominant mode of the

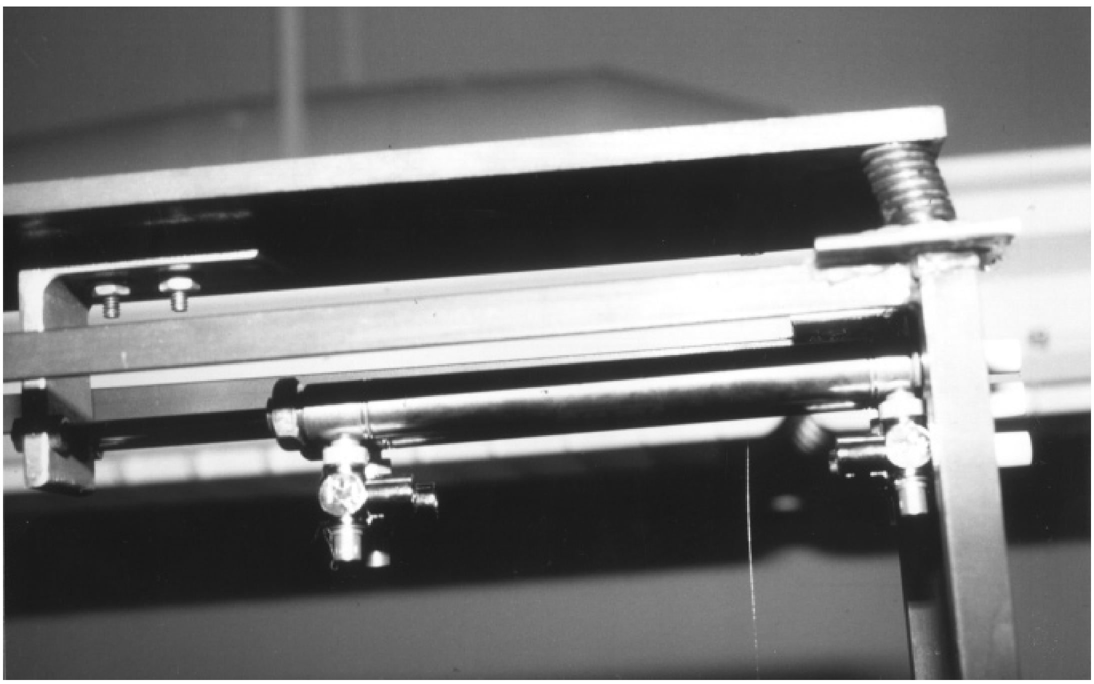

Figure 3. Close-up view of frame's top showing dampers and top plate mounted on rubber bearings

Table I. Analytically obtained modal dynamic properties of experimental frame without top plate

Mode	Frequency (Hz)	Participation factor	Unit-participation-factor generalized mass (kg)	Unit-participation-factor modal amplitude at roof level
1	2·53	0·298	15·60	1·40
2	9·30	0·114	2·28	0·67
3	19·7	0·062	0·70	0·43

structure, the vibration absorber system is tuned to this fundamental mode. The lateral stiffness and maximum damping constant for the vibration absorber system are determined using the design recommendations given by Villaverde and Koyama.[2] Assuming a 2 per cent damping ratio for the frame, considering that the isolation system is tuned to the fundamental frequency of the frame with no top plate, using the frame's top plate as the mass of the vibration absorber system, and following such recommendations, it is found that a lateral stiffness of 1·83 N/mm (10·42 lb/in) and a damping constant of less than 0·224 N s/mm (1·28 lb s/in) (corresponding to a damping ratio of 97 per cent) are needed to construct an efficient vibration absorber. Accordingly, four rubber bearings (one for each column) with stiffness of 0·458 N/mm (2·61 lb/in) each and 4 dampers (two for each side of the frame) with a damping constant of 0·025 N s/mm (0·14 lb s/in) each are selected for the construction of the vibration absorber system. It is noted that these 4 dampers furnish the vibration absorber system with a damping ratio of 42 per cent and the structure, according to Villaverde and Koyama's theory,[2] with a supplemental damping ratio of approximately 21 per cent. A damping ratio of less than the allowable maximum is selected because, as is well known, any increase in a structure's damping ratio beyond about 20 per cent cannot bring a substantial reduction in its dynamic response.

Since the required bearing size is not commercially available (too small), the rubber bearings are built in house using rubber pieces and steel washers glued together with a chemical compound that bonds rubber to metal. Six cylindrical rubber pieces with an outside diameter of 11·1 mm (7/16 in), inside diameter of 6·4 mm (1/4 in), and thickness of 1·6 mm (1/16 in); and six standard, plain steel washers with an outside diameter of 12·7 mm (1/2 in), an inside diameter of 5·6 mm (7/32 in), and a nominal thickness of 1·2 mm (3/64 in) are used to form the laminated bearings. In addition, a steel washer with an outside diameter of 31·8 mm ($1-\frac{1}{4}$ in), an inside diameter of 5·6 mm (7/32 in), and a thickness of 0·79 mm (1/32 in) is used as a base plate. The bearings are thus approximately 17·5 mm (11/16 in) in height. The rubber employed to fabricate the rubber pieces is a super-soft neoprene rubber with a tensile strength of 1·4 MN/m^2 (200 psi) and a durometer (shore) hardness between 5 and 10. In a shear test, a solid circular piece of this rubber 25·4 mm (1 in) in diameter and 1·6 mm (1/16 in) thick exhibited an essentially linear behaviour and a shear modulus of elasticity of 0·08 MN/m^2 (11·9 lb/in^2) up to a strain of 220 per cent. The chemical compound used to bond the rubber pieces to the washers and to the base plate is an epoxy-based structural adhesive named Fusor 320/310B and produced by Lord Corporation of Erie, PA. To enhance the bonding process, the rubber pieces are pre-treated with Chemlok 7701, a surface conditioner also produced by Lord Corporation. The process to construct the bearings consisted of (a) pre-treating the rubber pieces with the surface conditioner, (b) applying a thin layer of the adhesive to the steel washers, (c) joining together alternatively one rubber piece and one washer, (d) holding all the components together by means of a screw trough the centre of the components and a tightened nut, and (d) heating the bearings for five minutes in an oven at 100°C (212°F). Figure 4 shows a picture of one of the finished bearings. A test in shear performed to verify the integrity of the bearings so formed produced the graph shown in Figure 5. A photograph of the deformed configuration of the tested bearing after 38 mm (1·5 in) of lateral displacement (218 per cent strain) is shown in Figure 6.

The dampers selected for the vibration absorber system are four 14·3-mm (9/16-in) bore double-acting air cylinders manufactured by Bimba Manufacturing Company of Monee, IL. They have a maximum stroke length of 101·6 mm (4 in) and a fully extended length of 292·1 mm (11·5 in). The cylinders are implemented with flow control valves to adjust at will their damping constant. They are also implemented with a rod clevis and a pinned bracket to minimize the

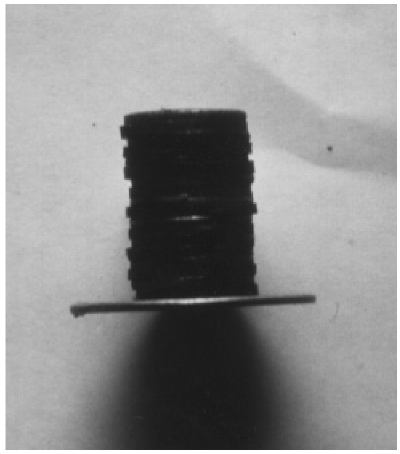

Figure 4. Laminated rubber bearings used in experimental study

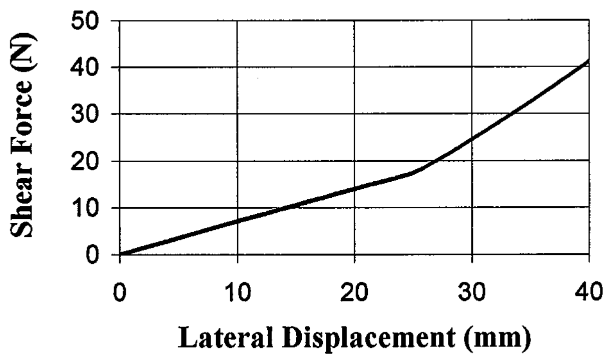

Figure 5. Force-displacement behaviour of laminated rubber bearing in shear test

damper's rod friction when the force applied to the damper is not colinear with the rod axis. For the experimental test herein reported, the dampers' flow control valves are closed five turns.

EXPERIMENTAL STUDY

In the experimental study, the frame is tested with and without the proposed vibration absorber system with a pair of shaking tables under sinusoidal excitations and a recorded earthquake ground motion. For these tests, the frame is mounted on the two shaking tables as shown in Figure 7. In addition to the shaking tables, the primary equipment used are an HP3562A dynamic signal analyser, accelerometers, string displacement transducers, and a data acquisition system. The shaking tables used have a horizontal surface of 228·6 mm $\times$ 304·8 mm (9 in $\times$ 12 in) and are driven by Electro-Seis electromagnetic shakers, models 113 and 400, from APS Dynamics, Inc.

Figure 6. Deformed configuration of laminated rubber bearing after 38 mm of shear deformation in shear test

Both have a capacity to support a vertical load of up to 320·6 N (72 lb) and a maximum stroke length of 158·7 mm (6·25 in). The two shaking tables are driven simultaneously according to a specified base acceleration by a personal computer implemented with a digital-to-analog converter board. The data acquisition system consists of a Macintosh computer and a computer program named Strawberry Tree, which automatically logs the output data.

Previous to the frame tests, the dynamic properties of the vibration absorber system are determined experimentally to verify it meets the specified requirements. First, the top plate and the bearings are mounted on the shaking tables and subjected, with the aid of the signal analyser, to a sine sweep. The purpose is to obtain the system's transfer function and to determine from this transfer function the undamped fundamental natural frequency of the system. From this test, it is found that the value of such natural frequency is equal to 2·65 Hz, which is close to the value of 2·53 Hz determined analytically for the frame and the value assumed in the design of the vibration absorber system. This test certifies that the way the rubber bearings are built leads, within reasonable limits, to the specified bearing properties. Subsequently, a second sine sweep test is performed with the air cylinders added to the plate-bearing system to estimate the damping ratio of the vibration absorber system. On the basis of the resulting transfer function and the half-power method, a damping ratio of 33 per cent is obtained. This value is, once again, close to the specified valued and a proof that the air cylinders are capable of adding the desired damping to the system.

The frame is also subjected to a series of sine sweep tests to determine its frequency response function and dynamic properties. In the first of such tests, the frame is tested in its conventional configuration; that is, without the rubber bearings and with its top plate mounted. Thereafter, the frame is tested with its top plate off first and then with its top plate mounted on the rubber bearings. The frequency response functions obtained are shown in Figure 8. Observe from this figure that the fundamental natural frequency of the frame without its top plate equals 2·375 Hz, which is off by about 6 per cent from the value of 2·53 Hz obtained analytically, and off by about 12 per cent from the value determined experimentally for the fundamental natural frequency of

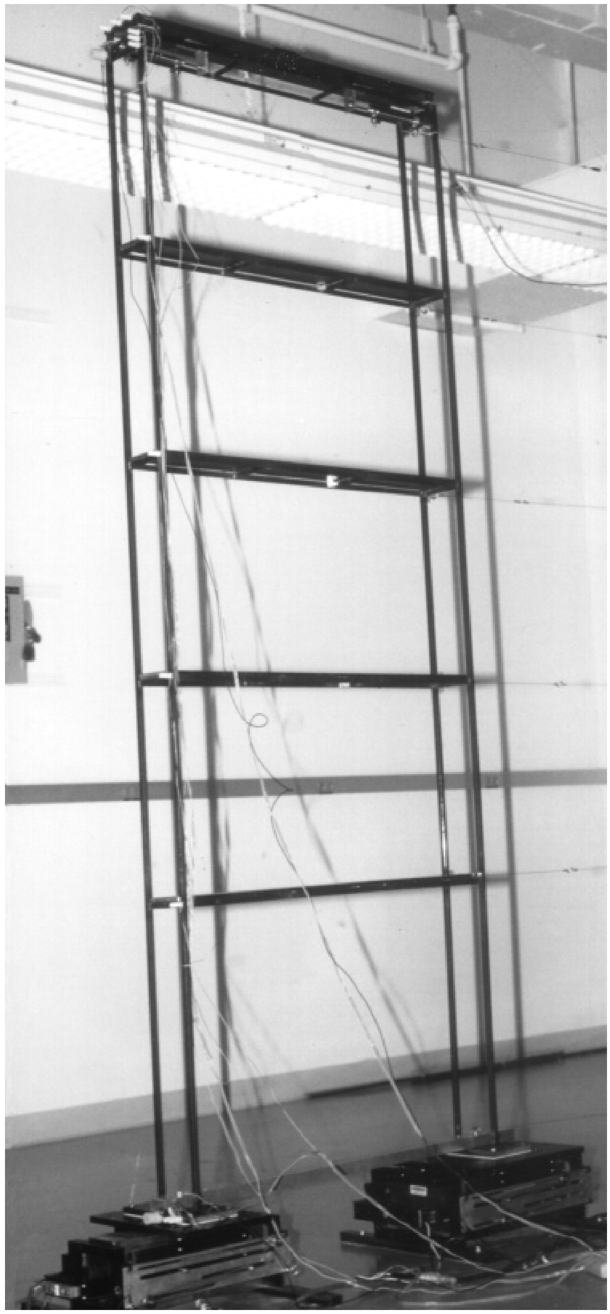

Figure 7. Set up of experimental model on shaking tables

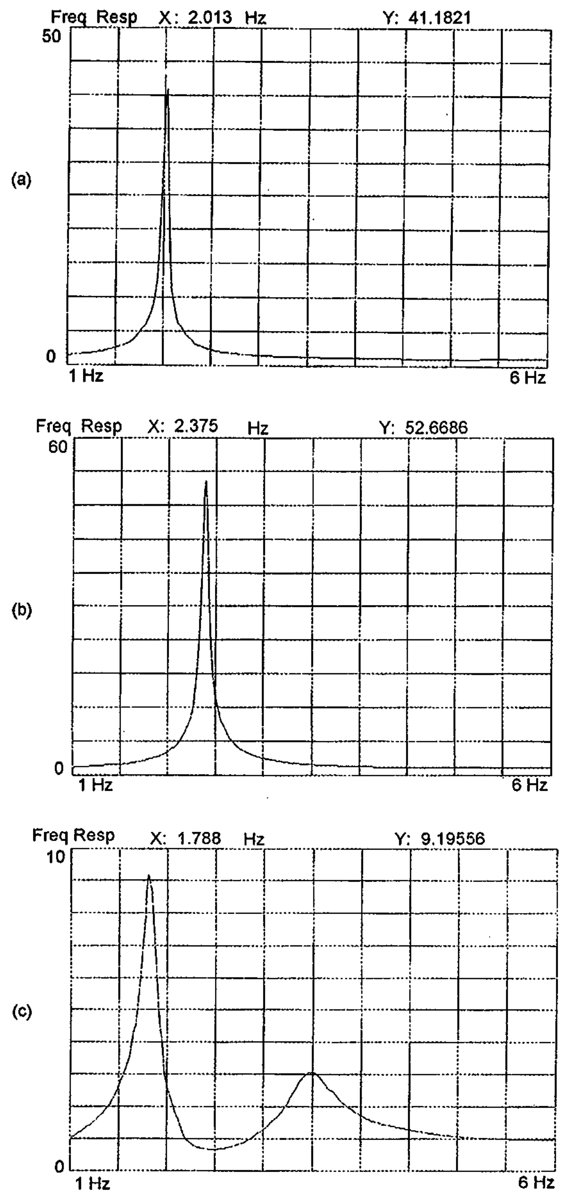

Figure 8. Frequency response function of experimental frame: (a) with conventional configuration; (b) with top plate off; and (c) with top plate mounted on rubber bearings

the vibration absorber system, i.e., 2·65 Hz. This means that the roof isolation system will not be perfectly tuned to the fundamental natural frequency of the frame. Although it would have been relatively easy to adjust the natural frequency of the frame to obtain a value that is closer to the natural frequency of the isolation system, it was decided not to change it in an effort to test

the effectiveness of the proposed isolation system when this system is not prefectly tuned to the fundamental natural frequency of the structure. It is believed that such a difference in natural frequencies may model more realistically a situation which may be often the case in real practice. Observe also from Figure 8 that when the frame's top plate is mounted on the rubber bearings, the frame possesses two closely spaced natural frequencies. The first equals 1·788 Hz and the second 3·488 Hz. According to Villaverde and Koyama's theoretical formulation,[2] this is an indication that the roof plate and the rubber bearings are working as anticipated, that is, as a vibration absorber.

The ground motion used in the shake table test that was performed to verify the effectiveness of the proposed roof isolation system corresponds to a modified version of the accelerogram recorded at Secretaria de Communicaciones y Transportes (SCT) during the 1985 earthquake in Mexico City. It is formed by truncating the first 20 s from this accelerogram and by considering only the following 20 s. In addition, its time axis is scaled by a factor of 0·198 to tune its dominant frequency to a frequency of 2·375 Hz, the experimentally determined fundamental natural frequency of the frame with its top plate off. The resulting ground motion and the corresponding displacement and acceleration response spectra are shown in Figures 9 and 10.

The Mexico City record was selected for this investigation because, in view of its nearly sinusoidal form, it is a record that can induce, when tuned to the fundamental natural frequency of the structure, a strong structural response. Given the limited capacity of the shaking tables used in the experiment, the use of this record was thus a way to test the model and the isolation system components under extreme conditions; i.e. large displacements and accelerations. Another reason was that, as shown in previous studies,[2–4] the effectiveness of a vibration absorber is more evident when a building is subjected to a damaging ground motion than when it is subjected to a ground motion that only induces an insignificant building response. Along the same lines, no other ground motions were considered in the experiment because it is known from the previous studies just referred to that vibration absorbers are effective to reduce the response of a structure under different ground excitations, particularly when the excitation is in resonance with the fundamental frequency of the structure. Besides, the objective of the investigation was to test whether or not the suggested isolation scheme can work effectively as a vibration absorber and not in demonstrating that vibration absorbers are effective under different earthquake excitations, which, again, is something that has already been discussed at length in an earlier publication.[2]

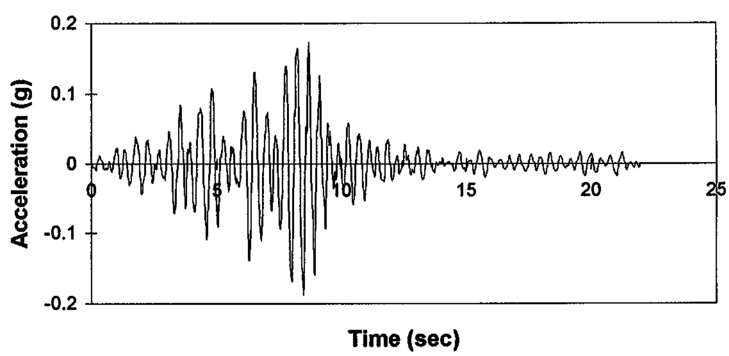

Figure 9. Ground motion considered in experimental study

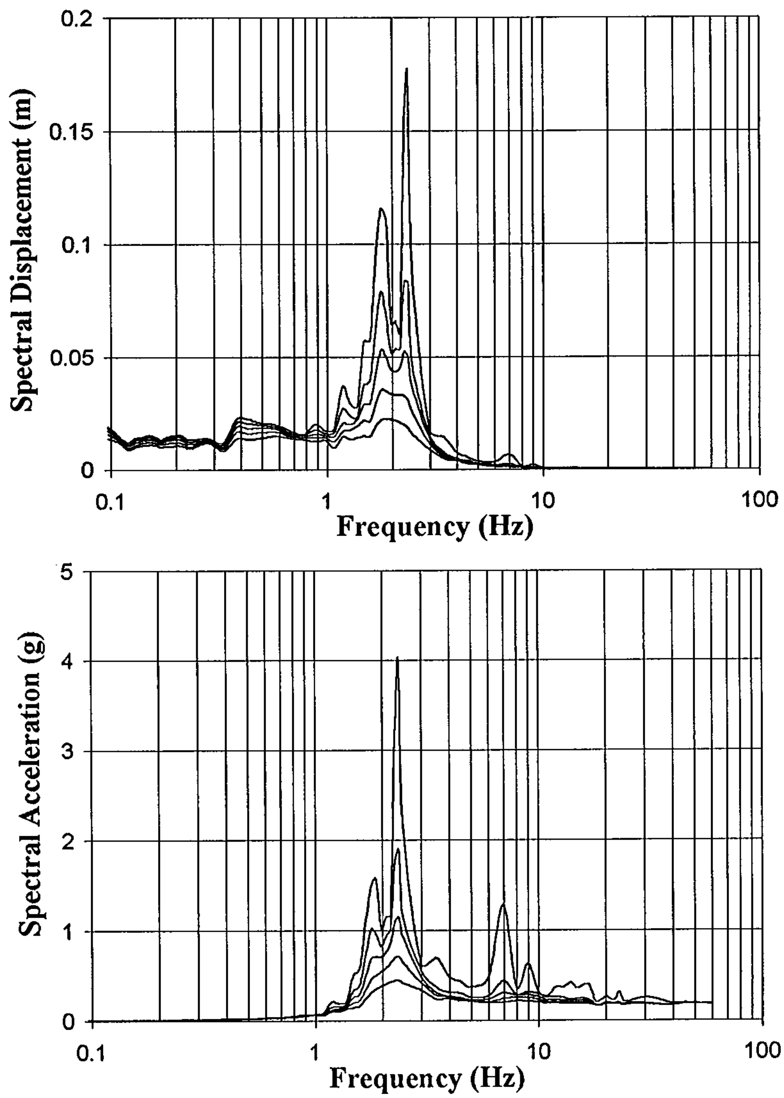

Figure 10. Displacement and acceleration response spectra of ground motion considered in experimental study for damping ratios of 0, 2, 5, 10, and 20 per cent of critical

In the final series of tests, the frame is subjected to the ground motion described above. The frame is tested first in its conventional configuration, and then with the isolation system in place. The time variation of the absolute floor accelerations and the absolute floor displacements (relative to a fixed reference frame) is captured in these tests. Some of the obtained results are presented in Figures 11 and 12 and Table II. Figure 11 shows the displacement (relative to the frame's base) and absolute acceleration time histories of the frame at the level of its fifth floor. Figure 11(a) displays those obtained when the frame is tested with its conventional configuration

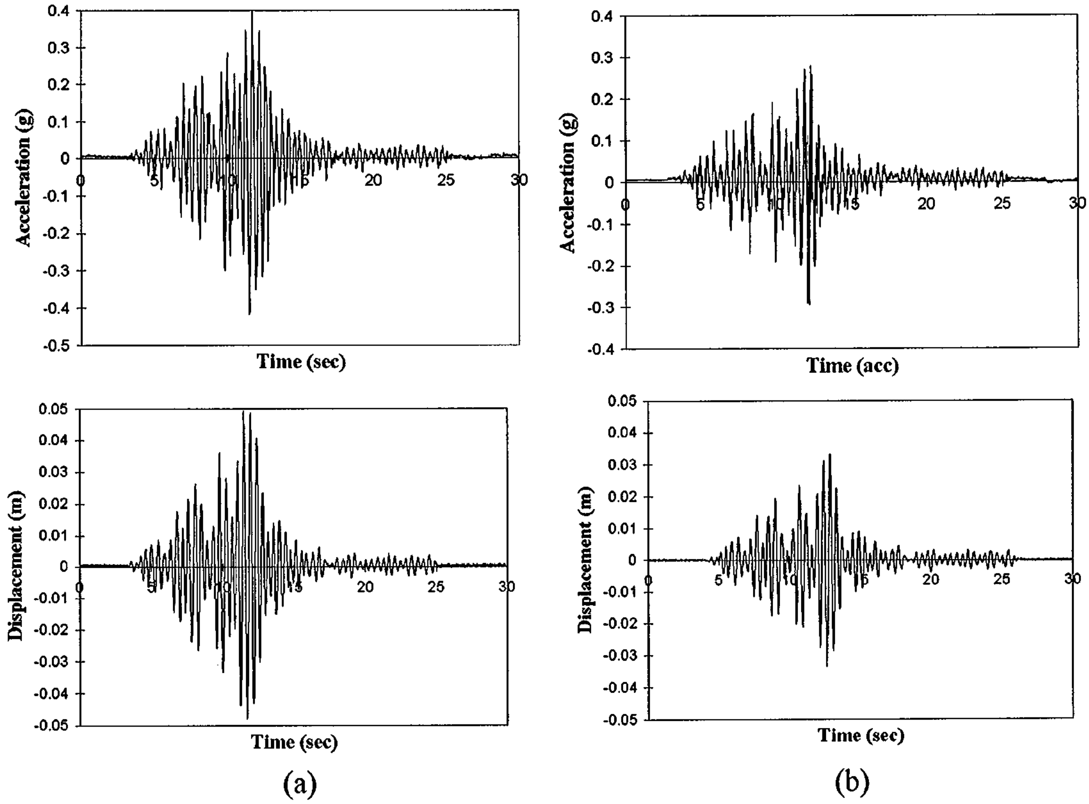

Figure 11. Accelerations and relative displacement time histories of fifth floor of frame with: (a) conventional configuration; and (b) roof isolation system

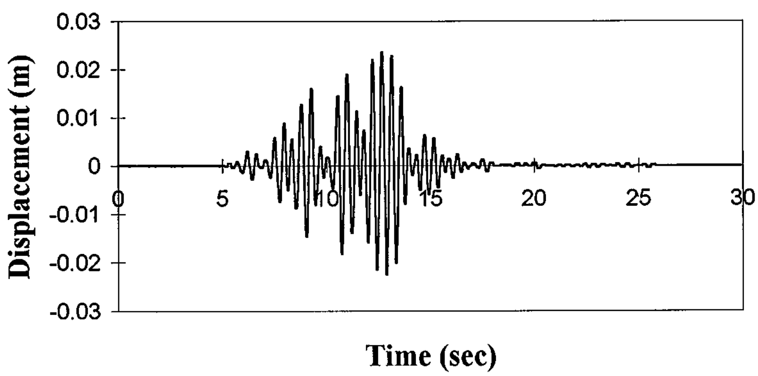

Figure 12. Displacement time history of top plate relative to fifth floor beams in frame with roof isolation system

Table II. Peak absolute accelerations and peak fifth-floor relative displacements of frame tested in experimental study with and without roof isolation system

Peak displacement (mm)			Peak acceleration (g)		
With no roof isolation	With roof isolation	Reduction (%)	With no roof isolation	With roof isolation	Reduction (%)
49·0	34·0	30·6	0·418	0·291	30·4

and Figure 11(b) those when the frame is tested with the configuration that includes the rubber bearings and the dampers. Note that in this latter case the displacements and accelerations are measured at the level of the fifth floor beams. Figure 12 depicts the time history of the displacements of the top plate relative to the fifth-floor beams when the frame is tested with the roof isolation system in place. This graph gives an indication of the deformations experienced by the bearings, which should normally be relatively large given that, by design, a vibration absorber system is always in resonance, or near resonance, with its supporting structure. Finally, Table II summarizes the performance of the vibration absorber system. This table shows the peak values of the fifth-floor displacements and accelerations obtained in each case and the percentages by which these peak values are reduced when the frame is implemented with the isolation system.

ANALYTICAL STUDY

It is well known that most structures are designed to yield under the effect of a strong earthquake. Hence, it is important that an investigation be made to determine how effective the suggested device may be after a structure implemented with it incurs into its non-linear range of behaviour. As mentioned earlier, however, the limitations in the capacity of the equipment made it impossible to test the experimental model under an excitation that would make its beams and columns undergo inelastic deformations. Therefore, such a question is explored using instead an analytical model of the frame.

For the purpose of the desired investigation, the frame is analysed under the effect of a series of progressively more severe ground excitations and its peak displacements and rotational ductilities compared for the cases when the frame is considered with and without the proposed roof isolation system. The analytical model used in this comparative study is essentially the same as the one utilized in the previous section for the calculation of the frame's modal properties. Similarly, the properties considered for the roof isolation system components are the same as those determined in that section on the basis of the design recommendations proposed by Villaverde and Koyama.[2] That is, it is considered that each of the four rubber bearings has a lateral stiffness of 0·458 kN/mm (2·61 lb/in) and that each of the four viscous dampers has a damping constant of 0·025 N s/mm (0·14 lb s/in). As established before, these properties correspond to a roof isolation system with a natural frequency of 2·53 Hz and a damping ratio of 42 per cent. For this study, however, the frame's beams and columns are modelled with bilinear beam elements, assuming a post-yield stiffness of one per cent of their initial, elastic stiffness, and considering a yield moment of 21·8 N m (192·4 lb in) for the beams and 84·9 N m (750·2 lb in) for the columns. In like manner, the rubber bearings are modelled with shear beam elements that

behave linearly up to a shear strain of 150 per cent. This assumption of a linear behaviour for the rubber bearings was justified on the basis of the monotonic shear test reported in the foregoing section (see Figure 5) and available experimental results from cyclic tests of full-scale natural rubber isolators,[8,9] such as the load-deformation curve shown in Figure 13. The analysis is carried out using a computer program for the non-linear analysis of two-dimensional frames,[10] after its modification to be able to consider structures that have different damping properties at different locations throughout the structure.

The ground motion used also corresponds to the same ground motion considered in the experimental study, except that it is affected instead by a time scale factor of 0·238. This time scale

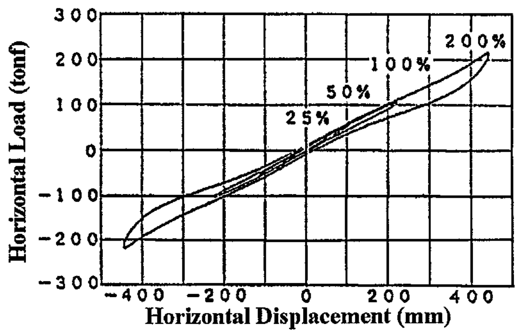

Figure 13. Load—deformation behaviour of natural rubber laminated bearings under shear strains below 200 per cent (Reproduced with permission from *Seismic Isolation and Response Control for Nuclear and Non-nuclear Structures*[8])

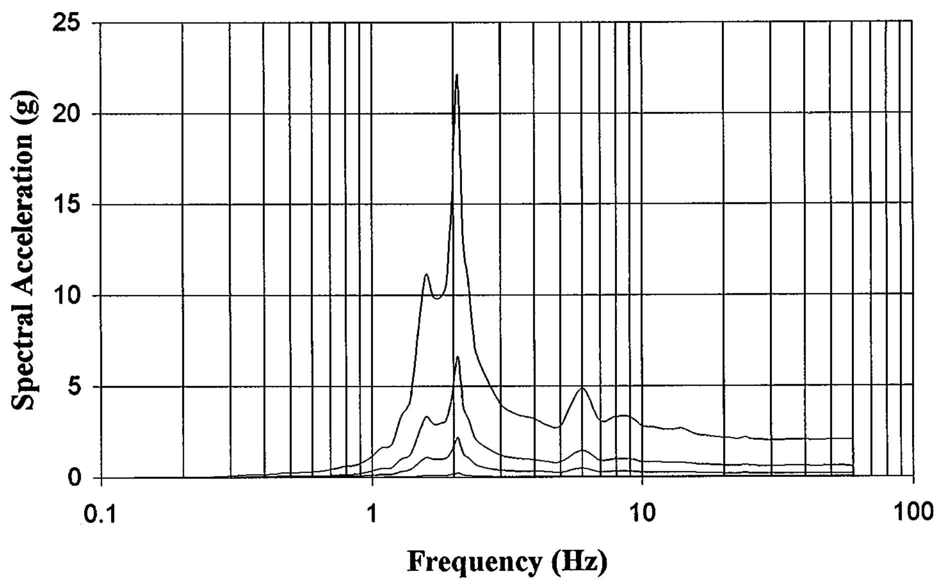

Figure 14. Two-per-cent damping elastic response spectra for ground motion considered in analytical study corresponding to scale factors of 0·11, 1·1, 3·3 and 11·0

factor produces a ground motion with a dominant frequency of 2·08 Hz, which corresponds to the analytically found fundamental natural frequency of the model in its conventional configuration. Another exception is that the ground motion accelerations are alternatively multiplied by a series of different scale factors with the purpose of studying the effectiveness of the roof isolation system under different response levels of the frame. The scale factors used were 0·11, 1·1, 3·3, and 11·0. The 2-per-cent damping elastic response spectra of the resulting ground motions are shown in Figure 14.

The results of the study are summarised in Table III. This table shows the maximum floor displacements obtained under the selected ground motions when the frame is considered with and without the roof isolation system. It also shows the corresponding rotational ductilities at the beams of each floor, where these rotational ductilities are defined as the maximum rotation at the beam end divided by the rotation that makes the beam yield. In addition, the table presents the percentages by which the roof isolation system reduces the displacements and rotational ductilities of the frame in each case. Observe from the results in Table III that the frame without the roof isolation system undergoes (a) purely elastic deformation in all its beams; (b) small inelastic deformations in some of its beams; (c) moderately large inelastic deformations in all its beams; and (d) large inelastic deformations in all its beams, respectively, when the considered ground motion is scaled by the factors of 0·11, 1·1, 3·3, and 11·0.

DISCUSSION OF RESULTS

An inspection of the results presented in Tables II and III reveals that the proposed roof isolation system substantially reduces the response of the studied frame. In the experimental study, the reduction factors are of the order of 30 per cent. In the analytical study, the maximum floor displacements are reduced, on average, by 84, 67, 37, and 41 per cent when the ground motion is considered with the scale factors of 0·11, 1·1, 3·3, and 11·0, respectively. Thus, a significant reduction in response is attained even when some members of the frame incur into their non-linear range of behaviour. As expected, though, the reduction in this latter case is not as large as when the structure behaves linearly at all times.

It may also be noted that the response reduction percentages obtained in the experimental study are not as large as those attained in the analytical study for the case when the structure behaves linearly. Several factors contributed to this difference. One of these factors is the fact that in the experimental study the vibration absorber system was not perfectly tuned to the fundamental natural frequency of the frame. It was noted previously that there was a difference of 12 per cent between the natural frequency of the experimental frame and that of the isolation system. It seems thus that this difference affected significantly the effectiveness of the isolation system. Another factor is the difference in the damping ratio of the vibration absorber system. In the experimental model, this damping ratio was 33 per cent. In the analytical study, it was 42 per cent. It is reasonable, thus, to have a smaller reduction in the response of the experimental frame. Still another factor is the non-linearity of the air cylinders used in the experiment and their deviation from being truly viscous. That is, because of friction and air compressibility, these air cylinders are far from being linear viscous dampers. Yet, they are assumed perfectly linear and perfectly viscous in the analytical study. It is likely, therefore, that this factor might have also contributed to the smaller response reduction observed in the experimental study.

Table III. Peak floor displacements and beam rotational ductilities of 5-storey frame in analytical study

Ground motion scale factor	Floor	Displacement in frame with no isolation (mm)	Displacement in frame with isolation (mm)	Displacement reduction (%)	Beam ductility in frame with no isolation	Beam ductility in frame with isolation	Beam ductility reduction (%)
	1	3·2	0·5	83	0·26	0·04	84
	2	7·1	1·2	84	0·29	0·05	84
0·11	3	11·0	1·8	84	0·26	0·04	84
	4	14·2	2·3	84	0·20	0·03	83
	5	16·6	2·7	84	0·14	0·03	81
	1	15·2	5·1	67	1·31	0·42	68
	2	35·1	11·7	67	1·47	0·46	69
1·1	3	54·9	17·8	68	1·31	0·41	69
	4	70·6	22·9	68	0·93	0·33	65
	5	81·8	26·7	67	0·66	0·27	59
	1	21·1	14·6	31	1·88	1·21	36
	2	50·3	33·0	34	2·35	1·36	42
3·3	3	81·0	50·8	37	2·25	1·21	46
	4	108·0	65·3	40	1·94	0·94	51
	5	128·3	75·9	41	1·57	0·75	52
	1	61·7	37·1	40	4·43	2·92	34
	2	127·0	79·5	37	5·37	3·29	39
11·0	3	200·7	121·7	39	6·09	3·34	45
	4	276·9	161·0	42	6·56	3·18	51
	5	365·8	198·1	46	6·41	2·98	54

The fact that the vibration absorber system was less effective in the experimental than in the analytical study should not be construed as an indication that proposed isolation system cannot perform exceptionally well under the constraints of the physical world. It should be considered instead that the system may also be quite effective in real buildings since in real buildings, unobstructed by the small scale of the tested experimental model, it is relatively easy to overcome the factors that hampered the system's performance in the experimental study. For example, one can (a) add or remove mass from the roof to closely tune the natural frequency of the vibration absorber system to the fundamental natural frequency of the structure; (b) use truly viscous dampers which in large sizes are commercially available; and (c) increase the system's damping ratio by increasing the number or capacity of the dampers incorporated into the system.

SUMMARY AND CONCLUSIONS

A roof isolation system that aims at reducing the response of buildings to earthquakes has been proposed and described. The system entails the insertion of flexible laminated rubber bearings between a building's roof and the columns that support this roof, and the addition of viscous dampers that connect the roof to a structural element below the roof. It is based on the idea of making the roof, rubber bearings, and viscous dampers, respectively, constitute the mass, spring, and dashpot of a vibration absorber. The details of and results from experimental and analytical studies conducted with a small-scale laboratory model with the purpose of assessing the feasibility and effectiveness of such an isolation system have also been presented. The results from the experimental study reveal that it is possible and relatively easy to implement a real structure with such a system and that it works effectively even when the properties and behaviour of its components deviate from the ideal properties and behaviour assumed in an analytical study. From the analytical study, it is found that the proposed system may significantly reduce the seismic response of a structure, even when the structure incurs into its non-linear range of behaviour. In view of these findings, it is concluded that the proposed roof isolation system may be physically realizable and effective in reducing the seismic response of buildings and has therefore the potential to become a practical and cost-effective alternative to reduce earthquake damage in buildings. It is concluded too that the system merits further studies to examine thoroughly its advantages and disadvantages and to find solutions to overcome some of the practical problems associated with it.

The study reported herein is part of a comprehensive investigation that has been undertaken to assess such advantages and disadvantages. Included in this investigation is an analytical study with an actual 13-storey building that will be conducted with the purpose of gaining an insight as to the size of the bearings and dampers that are needed to build an effective roof isolation system in real buildings, the space required to accommodate such bearings and dampers, the magnitude of the deformations experienced by the bearings, and the overall difficulties involved in the design and implementation of such a technique. It also includes a study to analyse and overcome the impact the isolation system may have on the architectural features of a building such as its water proofing, pipes and ducts, and stairways and elevators. This latter investigation will be conducted in response to an awareness of these unquestionable disadvantages of the system and the confidence, judging from the experience with base isolated buildings, that such a disadvantage may be overcome in a relatively easy and cost effective way.

Finally, it should be mentioned that, as proposed, the suggested isolation system can only be effective in buildings for which their roof weight represents a significant percentage of their total weight. Since it has been found in previous studies that an effective vibration absorber requires a mass of the order of 7 per cent of the total mass of the building where it is installed, this means that without an added mass the proposed isolation system can only be effective for buildings with up to about 15 stories. In like manner, it is important to note that the applicability of the system is limited to buildings which are not closely surrounded by neighbouring buildings at their roof level. That is, buildings that have the sufficient clearance to permit the unrestricted motion of the bearings. Thus, the proposed isolation system may not be a viable technique for all buildings but it may be an attractive one for a large number of them.

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